

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.						
1. REPORT DATE (DD-MM-YYYY) 13-11-2005		2. REPORT TYPE Final		3. DATES COVERED (From - To) Oct 2003 -- Sep 2004		
4. TITLE AND SUBTITLE Numerical Studies of Acoustic Propagation in Shallow Water				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER N00014-96-1-0790		
				5c. PROGRAM ELEMENT NUMBER		
				5d. PROJECT NUMBER		
6. AUTHOR(S) John B. Schneider				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Washington State University P.O. Box 642752 Pullman, WA 99164-2752				8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Code 3210A 800 N. Quincy St. Arlington VA 22217-5660				10. SPONSOR/MONITOR'S ACRONYM(S) ONR		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A Approved for Public Release Distribution Unlimited						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT Equations were derived which rigorously codify the propagation of fields in finite-difference time-domain (FDTD) grids. These equations were then used to construct a perfect total-field/scattered field boundary (which is used to inject energy into the grid). Algorithms were developed to enhance the modeling of material boundaries in the FDTD method; the accuracy of various FDTD or FDTD-like algorithms were rigorously studied; an FDTD algorithm was developed which is theoretically exact (i.e., provided the grid is infinite the accuracy is limited only by the finite precision of computers); various computer programs related to the FDTD method were written; and information and programs were disseminated via journal publications, conference presentations, and the Web.						
15. SUBJECT TERMS FDTD techniques, acoustic propagation and scattering						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT		18. NUMBER OF PAGES	
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	UU		5	
					19a. NAME OF RESPONSIBLE PERSON John B. Schneider	
					19b. TELEPHONE NUMBER (Include area code) 509 335 4655	

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Final Report: Numerical Studies of Acoustic Propagation in Shallow Water

John B. Schneider

School of Electrical Engineering and Computer Science

Washington State University

P.O. Box 642752

Pullman, WA 99164-2752

phone: (509) 335-4655 fax: (509) 335-3818 email: schneidj@eecs.wsu.edu

Award Number: N00014-96-1-0790

<http://www.eecs.wsu.edu/~schneidj/>

The FDTD method is obtained by discretizing the differential equations that govern the underlying system. Using a Cartesian grid, the method provides an exceedingly simple way in which to express future fields (i.e., unknown fields) in terms of past fields (known fields). For propagation in a homogeneous region, the traditional FDTD method is accurate to second-order—that is, doubling the number of grid points per wavelength reduces inherent numerical errors by a factor of four.

The behavior of fields and accuracy of the FDTD method at material interfaces are much more complicated than in a homogeneous region. We previously derived exact expressions describing the behavior of plane waves at planar boundaries [1,2]. Additionally we have examined and developed ways to minimize the errors associated with the “stairstep approximation” which is inherent when modeling continuously varying surfaces in the FDTD method [3-8]. The work most recently published in *The Journal of the Acoustical Society of America* showed how employing a simple modification of the equations used to update the fields adjacent to a rigid boundary could significantly improve the accuracy of the simulation [8].

We continued to explore several new implementations of the FDTD method (proposed by others) which seek to minimize dispersive and anisotropic errors inherent in all 2- and 3-D FDTD schemes. Our comparisons provide insight into the techniques that are not easily garnered from the publications in which they were originally presented. Some of this work appeared in *IEEE Transactions on Microwave Theory and Techniques* [9] and was presented at the 2002 URSI/Antennas and Propagation Symposium [10]. Notably, we demonstrated that many of the wavelet-based schemes, which have attracted some advocates, are not superior to an FDTD scheme that uses the same spatial stencil and the same “computational effort” (i.e., operations per a given temporal advancement of the fields). We have further expanded on this work in a recent publication [11].

Our investigations of the discretized worlds of FDTD methods have led us to a better understanding of numeric artifacts associated with resonances and to ways of alleviating these artifacts. Part of this work was presented as an invited talk in a special session organized by Prof. Allen Taflov (one of the co-founders of the FDTD method) [12]. This work is further described in a paper which has recently appeared in *IEEE Transactions on Antennas and Propagation* [13]. In that work we show how the anisotropic dispersion inherent in the traditional “Yee” FDTD algorithm can cause rather bizarre behavior in the resonant modes of a canonical resonator. Modes which are degenerate in the continuous (or “real”) world can split into multiple modes. On the other hand, modes which are distinct in the continuous world may be degenerate in the discrete FDTD world.

Additionally, even modes that are not split or recombined in some spurious manner in the FDTD world can nevertheless be shifted from the true resonant frequency that pertains in the continuous world. Our work provides a way to quantify this behavior exactly without ever needing to perform an FDTD simulation.

Given this understanding of the traditional FDTD technique, we were motivated to explore a technique which was more isotropic than the traditional FDTD technique. Thus, we developed a variation of the promising FDTD scheme proposed by Eric Forgry (*IEEE Transactions on Antennas and Propagation*, **50**(7):983–996, 2002). This algorithm suffers much less grid dispersion and anisotropy than more traditional FDTD formulations but still retains the local nature of the standard update equations. The acoustic implementation of this algorithm is described in a paper was published in the *Journal of Computational Acoustics* [14].

A recent publication by John Pendry (*Phys. Rev. Lett.*, **85**:3966, 2000) which described the use of backward-wave (BW) materials to make a “perfect lens” has received considerable attention. BW materials are dispersive materials whose direction of phase propagation is antiparallel to the direction of power flow. BW materials can exist in both acoustic and electromagnetic systems. BW materials belong to the class of materials know as “metamaterials” since they do not occur in nature (i.e., they must be manufactured). There is great interest in metamaterials since they can have interesting and useful properties not found in natural materials. Our initial attempts to model BW materials using the FDTD technique were not consistent with those one would expect from an initial inspection of the theory. Eventually we discovered that the dual, offset grids employed in the FDTD method (i.e., the dual pressure and velocity grids or the dual electric and magnetic field grids) can introduce significant numeric artifacts when modeling BW materials. The offset in the grids can introduce a boundary layer that has the material properties of neither the BW material nor the surrounding medium. Our investigations were presented in an invited talk at the 2002 URSI/Antennas and Propagation Symposium [15] and in a paper which was published in *Physical Review Letters B* [16]. These publications focused on the behavior of fields in the continuous world when a BW material has a small boundary layer. A recent publication in *IEEE Transactions on Antennas and Propagation* described specific implementation issues concerned with modeling BW materials using the FDTD method [17]. It was shown that the Pseudospectral Time-Domain (PSTD) method, which employs a collocated grid and uses discrete Fourier transforms to calculate spatial derivatives, may provide superior results to the FDTD method when modeling these materials.

The Yee FDTD algorithm can provide exact solutions to one-dimensional problems when operated at the so-called magic time step (i.e., when the spatial step size is equal to the speed of light times the temporal step size). Here “exact” is taken to mean the field propagates without dispersion error or other numeric artifacts beyond those which are dictated by the finite precision of the computer. Unfortunately there is no magic time step in higher dimensions. However we have recently developed a theoretical framework for multi-dimensional algorithms that have the same exact properties as the one-dimensional Yee algorithm when operated at a particular time step. The proposed technique uses vector operators which, instead of being defined at a point such as with the usual gradient, divergence, and curl operators, are defined over spheres. Due to their inherent symmetry, these spatial operators have the same properties in all directions. With

a judicious choice of the temporal step size the temporal errors can cancel the spatial errors and the algorithm is exact. However, although the framework for the algorithm has been developed, no practical (i.e., computationally efficient) algorithm has yet been developed. It should also be noted that the method is only theoretically exact on an infinite grid—a finite grid will introduce some inherent error but that error will be smaller than traditional FDTD techniques. Nevertheless proof-of-concept implementations of the algorithm (which are quite computationally expensive) have been used to demonstrate the validity of the technique and the improvements the algorithm can provide over other FDTD implementations. The algorithm also has interesting properties such as unconditional stability for an arbitrary temporal step size. Some of our work on this algorithm was presented as an invited talk at the 2003 URSI/Antennas and Propagation Symposium [18]. This work is further described in a publication in *Journal of Computational Physics* [19] and a Ph.D. dissertation (the author of which was partially supported under this grant) [20].

The understanding we have obtained of the FDTD method has provided a complete quantification of the way in which plane waves propagate in the discrete FDTD world. Using this knowledge we were able to construct an enhancement to the total-field/scattered-field boundary, which is a boundary used to introduce field into the FDTD grid. This enhancement, which is nominally exact, can provide an enormous improvement over the traditional implementation (better than a 100 dB reduction in errors in many situations). This work is described in a paper published in *IEEE Transactions on Antennas and Propagation* [21]. Additionally Prof. Taflovie invited the PI to contribute a section to the 2005 edition of his FDTD book [22] which has come to be regarded as the authoritative source for FDTD-related information.

Throughout the grant period we maintained a Web site, www.fdtdd.org, that seeks to list all archival publications related to the FDTD method. This site solicits input, in the form of comments posted about work appearing in the archival literature, from the entire community interested in the FDTD method (whether applied to acoustics, electromagnetics, or solid mechanics). We have also made code available there which can be used to solve various propagation problems.

REFERENCES

- [1] J. B. Schneider and R. J. Kruhlak, "Plane Waves and Planar Boundaries in FDTD Simulations," IEEE AP-S International Symposium and URSI Radio Science Meeting, Salt Lake City, UT, Jul. 2000.
- [2] J. B. Schneider and R. J. Kruhlak, "Dispersion of Homogeneous and Inhomogeneous Waves in the Yee Finite-Difference Time-Domain Grid," *IEEE Trans. Microwave Theory and Techniques*, vol. 49, no. 2, pp. 280–287, 2001.
- [3] F. D. Hastings, J. B. Schneider, and S. L. Broschat, "A Monte Carlo FDTD Technique for Rough Surface Scattering," *IEEE Trans. Antennas Propagat.*, vol. 43, no. 11, pp. 1183–1191, 1995.
- [4] F. D. Hastings, J. B. Schneider, and S. L. Broschat, "A Finite-Difference Time-Domain Solution to Scattering from a Rough Pressure-Release Surface," *J. Acoust. Soc. Am.*, vol. 102, no. 6, pp. 3394–3400, 1997.
- [5] J. B. Schneider, C. L. Wagner, and R. J. Kruhlak, "Simple Conformal Methods for FDTD Modeling of Pressure-Release Surfaces," *J. Acoust. Soc. Am.*, vol. 104, no. 6, pp. 3219–3226, 1998.
- [6] F. D. Hastings, J. B. Schneider, S. L. Broschat, and E. I. Thorsos, "An FDTD Method for

Analysis of Scattering from Rough Fluid-Fluid Interfaces,” *IEEE Journal of Oceanic Engineering*, vol. 26, no. 1, pp. 94–101, 2001.

[7] J. B. Schneider and J. G. Tolan, “A Locally Conformal Method for Modeling Rigid Boundaries in the FDTD Method,” *J. Acoust. Soc. Am.*, vol. 108, no. 5, pt. 2, pp. 2563, Newport Beach, CA, Dec. 2000.

[8] J. G. Tolan and J. B. Schneider, “Locally Conformal Method for Acoustic Finite-Difference Time-Domain Modeling of Rigid Surfaces,” *J. Acoust. Soc. Am.*, vol. 114, no. 5, pp. 2575–2581, 2003.

[9] K. L. Shlager and J. B. Schneider, “Comparison of the Dispersion Properties of Several Low-Dispersion Finite-Difference Time-Domain Algorithms,” *IEEE Trans. Antennas Propagat.*, vol. 51, no. 3, pp. 642–653, 2003.

[10] K. L. Shlager and J. B. Schneider, “A 2-D Dispersion Analysis of the W-MRTD Method Using CDF Biorthogonal Wavelets,” *IEEE AP-S International Symposium and URSI Radio Science Meeting*, vol. 3, pp. 244–247, San Antonio, TX, Jun. 2002.

[11] K. L. Shlager and J. B. Schneider, “Comparison of the Dispersion Properties of Higher-Order FDTD Schemes and Equivalent-Sized MRTD Schemes,” *IEEE Trans. Antennas Propagat.*, vol. 51, no. 3, pp. 642–653, 2003.

[12] C. L. Wagner and J. B. Schneider, “Using the Dispersion Relation to Understand Finite-Difference Time-Domain Worlds,” *International Conference on Electromagnetics in Advanced Applications (ICEAA 01)*, Torino, Italy, pp. 375–378, Sep. 2001.

[13] C. L. Wagner and J. B. Schneider, “On the Analysis of Resonators Using Finite-Difference Time-Domain Techniques,” *IEEE Trans. Antennas Propagat.*, vol. 51, no. 10, pp. 2885–2890, 2003.

[14] C. L. Wagner and J. B. Schneider, “An Acoustic Finite-Difference Time-Domain Algorithm with Isotropic Dispersion,” accepted for publication in *J. Computational Acoust.*

[15] M. W. Feise, P. J. Bevelacqua, and J. B. Schneider, “Backward-Wave Meta-Materials for Perfect Lenses,” *IEEE AP-S International Symposium and URSI Radio Science Meeting*, San Antonio, TX, Jun. 2002.

[16] M. W. Feise, P. J. Bevelacqua, and J. B. Schneider, “Effects of Surface Waves on the Behavior of Perfect Lenses,” *Physical Review B*, vol. 66, no. 3, 035113 (five pages), 2002.

[17] M. W. Feise, J. B. Schneider, and P. J. Bevelacqua, “Finite-Difference and Pseudospectral Time-Domain Methods Applied to Backwards-Wave Metamaterials,” *IEEE Trans. Antennas Propagat.*, vol. 52, no. 11, pp. 2955–2962, 2004.

[18] C. L. Wagner and J. B. Schneider, “Toward the Creation of a Magic Time Step in Three-Dimensional FDTD Algorithms,” *IEEE AP-S International Symposium and URSI Radio Science Meeting*, Columbus, OH, Jun. 2003.

[19] C. L. Wagner, “Theoretical Basis for Numerically Exact Three-Dimensional Time-Domain Algorithms,” *J. Comp. Phys.*, vol. 205, no. 1, pp. 343–356, 2005.

[20] C. L. Wagner, “Theoretical Basis for Numerically-Exact Three-Dimensional Time-Domain Algorithms,” Pullman, WA, Washington State University, 2004.

[21] J. B. Schneider, “Plane Waves in FDTD Simulations and a Nearly Perfect Total-Field/Scattered-Field Boundary,” *IEEE Trans. Antennas Propagat.*, vol. 52, no. 12, pp. 3280–3287, 2004.

[22] J. B. Schneider, "Advanced Dispersion Compensation in the TF/SF Technique," Sec. 5.9 of *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, 3 ed., A. Taflové and S. Hagness, Boston, MA, Artech House, 2005.